Future Circular Collider Study (FCC)

TOBIAS GOLLING

Université de Genève, 24, Quai Ernest-Ansermet - CH-1211 Genève 4 - Switzerland

Tobias.Golling@unige.ch

Abstract. The status and plans for the Future Circular Collider (FCC) design study are presented. The ultimate goal, and the emphasis for the infrastructure, is a proton-proton machine operating at a center-of-mass energy of 100 TeV in a 100-km ring in the Geneva area, called FCC-hh. A stepping stone to this machine is a high-luminosity electron-positron collider (called FCC-ee) using the same ring with center-of-mass energies ranging from the Z pole to the t̅t threshold. The main goal is an extended search for physics beyond the Standard Model as well as a complete exploration of the Higgs boson and its dynamics.

INTRODUCTION

The LHC Run 1 gave us the Higgs bosons discovery [1], Run 2 is in full swing, and with the High Luminosity upgrade the LHC has a physics program until the year 2035. What is the next leap forward in collider physics? Are there physics opportunities beyond the LHC? The Future Circular Collider (FCC) design study explores the post-LHC particle accelerator options in a global context. It entails an in-depth analysis of infrastructure, operation concepts and technologies necessary to build such a future circular collider. The physics opportunities are evaluated for a proton-proton machine operating at a center-of-mass energy of 100 TeV (FCC-hh) and a high-luminosity electron-positron collider (FCC-ee) with center-of-mass energies ranging from the Z pole to the t̅t threshold. Both would use the same ring, with a circumference of about 100 km, to be built in the Geneva area at CERN. There is also an option for an electron-proton collider (FCC-he), which would in particular allow one to resolve the proton structure and associated parton distribution functions more than one order of magnitude deeper into matter than what HERA could do.

The FCC collaboration is currently composed of 68 institutes and 26 countries [2] (status of December 2015). A conceptual design report will be delivered before the end of 2018, in time for the next update of the European Strategy for Particle Physics.

The FCC study started officially in the beginning of 2014 with a Future Circular Collider Study Kick-Off Meeting at the University of Geneva [3]. Annual Meetings of the Future Circular Collider study (FCC Weeks) [4, 5] are planned once a year until the conceptual design report in 2018.

It appears early to start the FCC activities now with the collider community fully focused on LHC’s Run 2 and the phase-2 detector research and development and construction activities ramping up. But history shows that large-scale projects like the LHC take about 20 years from the first design through construction up to the first physics results. If the goal is to have a first version of the FCC ready in 2035 then its preparation has to start now. In fact many workshops and meetings take place where FCC detector needs and physics benchmarks are discussed [6]. This ongoing activity can be followed on indico, see for instance Ref. [7] regarding the FCC-hh physics and detector activities. In this report a few selected and representative physics benchmarks studies will be given to illustrate the ongoing activities.

FCC-hh vs. LHC and FCC-ee vs. LEP

A collider’s center-of-mass energy is proportional to the dipole magnetic field and the radius. In order to achieve a center-of-mass energy of 100 TeV, which is about one order of magnitude higher than the LHC’s design energy of 14 TeV an increase in the radius by a factor of about 4 and an increase in the dipole magnetic field by a factor of about 2 are envisioned. The ultimate goal for the integrated luminosity of the FCC-hh is 10-20 ab⁻¹. More information is given in Tables 1 and 2, which show the currently considered design parameters for the FCC-hh and FCC-ee, respectively.
TABLE 1. Design parameters of the FCC-hh in comparison with LHC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-of-mass energy [TeV]</td>
<td>100</td>
<td>14</td>
</tr>
<tr>
<td>Dipole field [T]</td>
<td>16</td>
<td>8.33</td>
</tr>
<tr>
<td>Number of interaction points (IP)</td>
<td>2 main, +2</td>
<td>4</td>
</tr>
<tr>
<td>Luminosity/IP_{main} [10^{34} cm^{-2} s^{-1}]</td>
<td>5 - 25</td>
<td>1</td>
</tr>
<tr>
<td>Stored energy/beam [GJ]</td>
<td>8.4</td>
<td>0.39</td>
</tr>
<tr>
<td>Synchrotron radiation [W/m/ aperture]</td>
<td>28.4</td>
<td>0.17</td>
</tr>
</tbody>
</table>

TABLE 2. Design parameters of the FCC-ee in comparison with LEP2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-ee</th>
<th>FCC-ee</th>
<th>FCC-ee</th>
<th>LEP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-of-mass energy [GeV]</td>
<td>90</td>
<td>240</td>
<td>350</td>
<td>210</td>
</tr>
<tr>
<td>Bunches/beam</td>
<td>13000 - 60000</td>
<td>500 - 1400</td>
<td>51 - 98</td>
<td>4</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>1450</td>
<td>30</td>
<td>6.6</td>
<td>3</td>
</tr>
<tr>
<td>Luminosity/IP [10^{34} cm^{-2} s^{-1}]</td>
<td>21 - 280</td>
<td>5 - 11</td>
<td>1.5 - 2.6</td>
<td>0.0012</td>
</tr>
<tr>
<td>Energy loss/turn [GeV]</td>
<td>0.03</td>
<td>1.67</td>
<td>7.55</td>
<td>3.34</td>
</tr>
<tr>
<td>Synchrotron power [MW]</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>22</td>
</tr>
<tr>
<td>RF voltage [GV]</td>
<td>0.3 - 2.5</td>
<td>3.6 - 5.5</td>
<td>11</td>
<td>3.5</td>
</tr>
</tbody>
</table>

**FCC-ee physics program**

The FCC-ee’s core physics program [8] is composed of Standard-Model precision measurements at center-of-mass energies between 90 and 350 GeV:

- the Z pole scan at a center-of-mass energy from 88 to 95 GeV allows one to make precision measurements of the mass $m_Z$ and width $\Gamma_Z$ of the Z boson down to 100 keV, $\alpha_s(m_Z)$ down to $10^{-4}$, $\alpha_{QCD}(m_Z)$ down to $2 \times 10^{-5}$, as well as to study rare decays and flavor physics with up to $10^{13}$ Z bosons, including e.g. the search for right-handed neutrinos.
- the WW threshold scan at a center-of-mass energy from 160 to 165 GeV provides an unprecedented precision of the W boson mass measurement to a level of 300 keV and $\alpha_s(m_W)$ to $10^{-4}$.
- the running scheme as a Higgs factory with a center-of-mass energy of 240 GeV and above is probably the centerpiece of the FCC-ee. It will considerably improve over the High Luminosity LHC precision on the Higgs couplings by an order of magnitude and allow for a measurement of the Higgs width to better than 1%, as well as the Higgs branching ratio to invisible particles down to 0.1%.
- the $t\bar{t}$ threshold scan at a center-of-mass energy from 340 to 350 GeV makes a measurement of the top quark mass possible with a precision of 10-20 MeV, as well as a $t\bar{t}Z$ coupling measurement in the sub-percent area.

**FCC-ee Higgs physics program**

The so-called recoil method is unique to lepton colliders and allows one to tag the Higgs event independent of the Higgs boson decay mode. Figure 1 shows the distribution of the mass recoiling against the lepton pair in the $e^+e^- \rightarrow HZ$ channel, in the $Z \rightarrow l^+l^-$ final state ($l = e, \mu$) corresponding to one year of data taking [9]. A fit is used to extract the number of Higgs boson events which allows one to measure the total $e^+e^- \rightarrow HZ$ production cross section with a precision of 0.4%.

Another unique measurement of FCC-ee is about the Higgs production in the $s$-channel which allows on measure directly the Higgs coupling to electrons, using various Higgs bosons decays modes. Preliminary studies predict sensitivity approaching the Standard Model Higgs-to-electron coupling with an integrated luminosity of order $10^{34}$ ab^{-1} [10].

**FCC-hh physics program**

The FCC-hh physics program is essentially composed of three pillars:
FIGURE 1. Distribution of the mass recoiling against the lepton pair in the $e^+e^- \rightarrow HZ$ channel, in the $Z \rightarrow l^+l^-$ final state ($l = e, \mu$), taken from Ref. [9], for an FCC-ee integrated luminosity equivalent to approximately one year of data taking at a center-of-mass energy of 240 GeV.

- direct searches for new high-mass physics objects as predicted by extensions of the Standard Model such as Supersymmetry or Composite Higgs models
- direct searches for rare new physics processes
- indirect probes of new physics by testing Standard Model predictions with high luminosity and rates

**FCC-hh and naturalness**

The so-called hierarchy problem, also known as the naturalness problem, has been the driving force over the past decades for the design of extensions of the Standard Model. The FCC-hh is a game changer regarding this pressing open question in the sense that the absence of new physics at the 100 TeV FCC-hh would correspond to a fine-tuning of the order of $10^{-4}$ - this is a level of tuning never seen in particle physics and according to N. Arkani-Hamed a “mortal blow to naturalness” [11].

**FCC-hh - Supersymmetry and Dark Matter**

Supersymmetry spectra with a pure wino LSP can be realized if anomaly mediation is the main mechanism through which the gaugino soft masses are generated. This scenario leads to small mass splittings between the chargino and neutralino of less than 1 GeV, which leads to the so-called disappearing-track signature. Extrapolations from corresponding ATLAS searches to the FCC-hh environment [12] show sensitivity to WIMPs well beyond 1 TeV in mass as can be seen in Figure 2.

In Ref. [13] a variety of Supersymmetry Simplified Models are studied with focus on strong production using final state signatures of jets + missing transverse energy, mono-jet signatures, or same-sign di-lepton approaches. In particular Table 21 of Ref. [13] compares the exclusion and discovery reach for the 14 TeV LHC and the 100 TeV FCC-hh, quantifying the extended reach. For instance assuming 3000 fb$^{-1}$ of integrated luminosity, a gluino that decays to light flavor quarks can be discovered below 2.3 TeV at the 14 TeV LHC and below 11 TeV at a 100 TeV machine.
FCC-hh and other Exotics Physics

The search for high-mass resonances is motivated by various new physics models, including models with Extra Dimension or a Composite Higgs boson. Here one example is given for the search of resonances decaying to dijets. Ongoing studies [14] quantify the discovery potential as a function of the mass of a color singlet vector resonance assuming a relative width of 1% and universal couplings to fermions. Figure 3 shows the dependence of the discovery reach on the detector energy resolution, assuming an integrated luminosity of 10 ab$^{-1}$. For an assumed jet energy detector resolution of 1% the discovery reach extends to resonance masses of about 35 TeV, while an assumed 10% detector resolution reduces this reach by about 10 TeV. As can be seen from this example, physics benchmarks represent a crucial input for the choice of the detector design.

Many hypothesized high-mass resonances are expected to decay to top quarks, $W$, $Z$ or $H$ bosons. The hadronic decays of these Standard Model particles have high branching fractions and the associated fully-hadronic final states are most promising to extend the discovery potential to the highest masses. The interesting $p_T$ range of these so-called “superboosted” top quarks, $W$, $Z$ or $H$ bosons extends to the multi-TeV range which brings new challenges and opportunities [15].

FCC-hh precision physics program

The direct searches for new physics are complemented with a strong FCC-hh precision physics program. Compared to the LHC’s center-of-mass energy of 14 TeV the Higgs production cross sections increase by at least a factor of 10 at 100 TeV, up to a factor of 42 for di-Higgs production and a factor of 61 for $t\bar{t}H$ production [10], resulting in FCC-hh Higgs data sets which are a factor of 10-400 larger than at the High Luminosity LHC. The FCC-hh Higgs physics program is largely complementary to the FCC-ee Higgs physics program and allows in particular to measure the top-Yukawa coupling with %-level precision.

The top quark offers another big opportunity for the FCC-hh to carry out precision measurements and probing rare decays with $10^{12}$ top quarks expected in 10 ab$^{-1}$ at 100 TeV, and associated $10^{12}$ bottom hadrons and $W$ bosons from the top quark decay. Furthermore searches for rare decays are made possible using a few times $10^{11}$ charm hadrons from the $W$ boson decays from the top quark, as well as $10^{11}$ leptons from the $W$ boson decays from the top quark, including e.g. searches for $\tau \rightarrow 3\mu$ or $\tau \rightarrow \mu\gamma$. This top quark physics program makes high demands on the
detector capabilities regarding in particular reconstructed physics objects with a $p_T$ in the range of 0.1-1 TeV.

**Challenges for physics with 100 TeV proton-proton collisions**

The exploration of physics beyond the Standard Model using proton-proton collisions with a center-of-mass energy of 100 TeV bears unprecedented challenges. In order to contain the highest $p_T$ jets (of tens of TeV) fully in the hadronic calorimeter a depth of at least 12 $\lambda$ is necessary. A calorimeter lateral segmentation in $\eta\phi$ of 0.05x0.05 or 0.025x0.025 is currently considered. This resolution is mainly driven by the needs to mitigate pileup and to measure the jet substructure for superboosted top quarks, $W$, $Z$ and $H$ bosons with transverse momenta in the multi-TeV range. Another challenge is the momentum resolution for multi-TeV muons. The size of the ATLAS detector [16], for instance, is driven by the size of the muon system with the goal to measure the transverse momentum of muons with $p_T = 1$ TeV with a 10% uncertainty, resulting in a diameter of ATLAS of about 25 m. Scaling this up to muons of $p_T = 10$ TeV with a similar target uncertainty pushes the size of the detector and of the magnetic field beyond feasibility and alternative strategies are needed and are being developed. Not only the design of the calorimeter and the muon system manifest challenges for the reconstruction of multi-TeV objects, but also the tracking system. Identification of $b$-jets or tau leptons with a $p_T$ well beyond the 1-TeV level has never been done before at a collider experiment. More generally, the high boost of Standard Model particles results in very collimated objects and makes high demands on tracking capabilities in very dense environments. The aforementioned physics benchmarks are used to specify the detector and identification needs. A fast simulation of different detector configurations and a close collaboration between physics analysis and detector design is crucial in this phase of the study.

**Conclusion**

This document just gives a glimpse of the ongoing activities to explore the physics opportunities for the FCC. A lot of work is still needed to complete a conceptual design report by the end of 2018. People interested in contributing are very welcome and are invited to contact the author or other organisers or conveners, see contacts e.g. in Ref. [6].
ACKNOWLEDGMENTS

The author wishes to thank Alain Blondel and Michelangelo Mangano for helpful input and discussions.

REFERENCES


[6] https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider (and hyperlinks on this twiki)


